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RADIO ASTRONOMY EXPLORER B ANTENNA ASPECT PROCESSOR

**WARNER H. MILLER
JOSEPH NOVELLO
CHARLES C. REEVES**

JULY 1972

GSFC

**— GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND**

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ABSTRACT

This paper describes the antenna aspect system used on the Radio Astronomy Explorer B spacecraft. This system consists of two facsimile cameras, a data encoder, and a data processor. Particular emphasis is placed on the discussion of the data processor, which contains a data compressor and a source encoder. With this compression scheme a compression ratio of 8 is achieved on a typical line of camera data. These compressed data are then convolutionally encoded.

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CONTENTS

	<i>Page</i>
ABSTRACT	iii
INTRODUCTION	1
DESCRIPTION OF RAE B LUNAR MISSION	1
Scientific Objective	1
Spacecraft Orbit	1
Antenna System	2
BOOMTIP VIEWING SYSTEM	2
VIDEO COMPRESSION SYSTEM	3
Limitations on RAE Telemetry	3
Required Compression Ratio	4
Required Picture Quality	4
Compression Technique	4
DATA STUDY BY COMPUTER	6
AAP SYSTEM	9
Data Compressor	10
Sector Memory	11
Output Buffer	12
Convolutional Encoder	12
Command Storage	14
Physical Parameters	15
ACKNOWLEDGMENTS	16
REFERENCES	16

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RADIO ASTRONOMY EXPLORER B ANTENNA ASPECT PROCESSOR

Warner H. Miller, Joseph Novello, and Charles C. Reeves
Goddard Space Flight Center

INTRODUCTION

This document describes the antenna aspect processor (AAP) for the Radio Astronomy Explorer B (RAE B) spacecraft. The antenna aspect system consists of two facsimile cameras, a data encoder, and a data processor that is used to compress camera data to a bandwidth compatible with the telemetry link. This system will provide data for determining the position of the tips of the four 229-m (750-ft) antenna booms with respect to the structure of the RAE B spacecraft and the celestial background.

This document describes in detail the source encoder and the compression scheme used. Also described is the AAP hardware.

DESCRIPTION OF RAE B LUNAR MISSION

Scientific Objective

The objective for RAE B is to make measurements at lunar distances of galactic and solar radio noise at frequencies below the ionospheric cutoffs of Earth and external to terrestrial background interference for approximately one lunar rotation. The measurements will be made at selected frequencies in the range from 0.03 to 20 MHz:

Although RAE 1 was a successful radio astronomy mission, several limitations were imposed on the RAE 1 by a near-Earth orbit. Conducting a similar experiment from lunar orbit will enhance the mission by providing more frequency coverage, and lunar occultation will give additional resolution.

Spacecraft Orbit

The RAE B spacecraft will be placed in an 1100-km circular retrograde orbit of the Moon with an inclination between 50° and 60° to the lunar equator, an eccentricity of less than 0.005, and a 225-min orbital period. The spacecraft will then be despun and the antenna array deployed to full length (229 m).

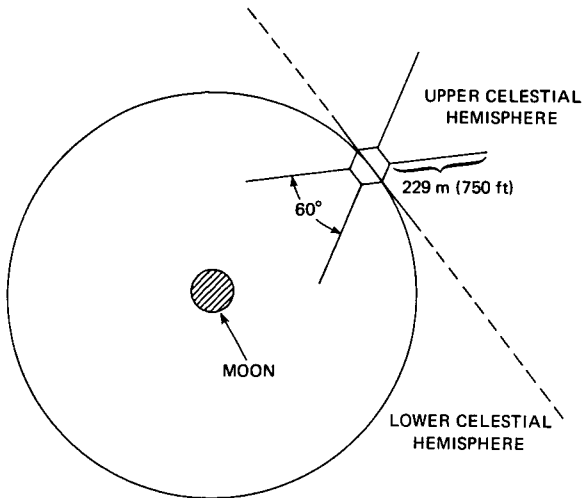


Figure 1.—Antenna V-boom orbit orientation. (Distances are not to scale.)

Antenna System

The experiment antennas will consist of two back-to-back V antennas formed by deploying four 1.27-cm (0.5-in.) diameter booms to maximum lengths of 229 m. The spacecraft will be gravity-gradient oriented. One V antenna will point toward the Moon, while the other antenna will point toward the upper celestial hemisphere. (See fig. 1.)

BOOMTIP VIEWING SYSTEM

The antenna aspect system (AAS) will consist of two facsimile cameras, a data encoder, and a data processor. The cameras will be mounted on solar paddle arms

and each camera will have a 70° by 360° field of view. The 360° scan will be parallel to the plane of the V booms and the 70° scan will be normal ($\pm 35^\circ$) to the plane of the V booms so that all four booms are within the field of view of each camera.

Figure 2 shows an expected RAE B antenna-aspect view as seen from a circular orbit 1100 km above the lunar surface. The 70° angle is scanned by the camera 512 times. Under these conditions, as much as 21 percent of the data in a scanned line is of the Moon.

Only one camera will be operating at a given time. Selection of the camera to be operated will be by a command from the ground station. The commands will also cause the

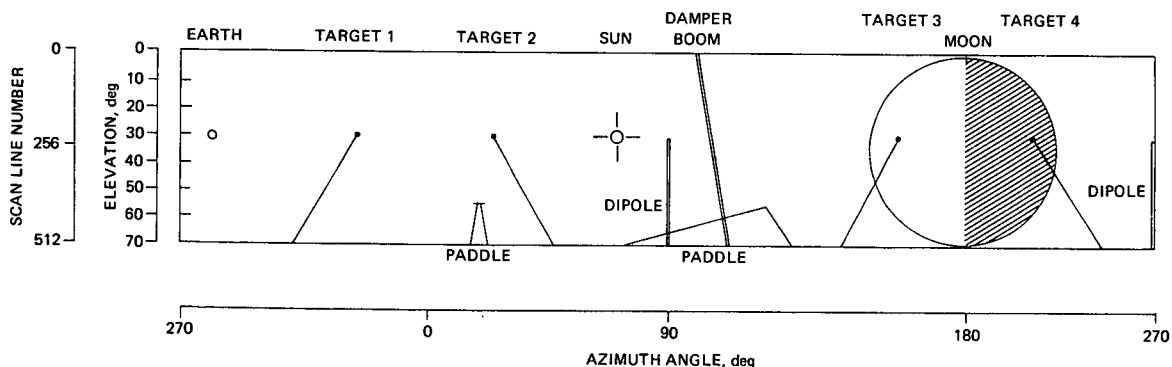


Figure 2.—Expected antenna-aspect view.

spacecraft to apply power to the encoder to start the system. The time required for one complete panoramic field of view will be 4.0 min. The AAS will be internally programed to turn off the camera and encoder at the end of each complete field-scan operation.

The video output of the camera is to be an amplified analog signal, which is wired to the encoder for processing. The encoder will count lines and provide digital identification of the line synchronization signal and line number, with digital encoding of the video signal throughout each scan line. The data will be formatted into a signal channel of combined digital synchronization, line identification, and video data.

VIDEO COMPRESSION SYSTEM

Limitations on RAE Telemetry

Table 1 summarizes a telemetry system calculation for the RAE B 400-MHz channel at lunar distance. The calculation shows that the received signal level available when transmitting at 625 bps will yield a signal-to-noise ratio (SNR) of 11.8 dB. The value of SNR is defined as the product of signal energy S and information period T divided by the noise power per hertz N . Table 1 shows that, with nominal conditions, the available SNR is 11.8 dB. This SNR will result in a probability of bit error (pbe) of 10^{-5} with no signal margin. Bit errors will affect the compressed data amplitude and timing information. An amplitude error would have little effect in determining the boomtip position; however, a timing error would propagate through a line of decompressed data and, if undetected, could lead to an erroneous boomtip position reading. Additional timing information could not easily be added

Table 1.—RAE B 400-MHz Telemetry-Link Analysis, Spacecraft to Ground

Signal:	
Transmitter power (6 W)	37.79 dBmW
Spacecraft antenna gain	0
Path loss (400 MHz at 3.85×10^5 km)	-196.04 dB
Receiver antenna gain (40 ft)	31.0 dB
Processing loss	-1.0 dB
Polarization loss	0
Maximum null level	-6.0 dB
Total received power	-134.25 dBmW
Power in sidebands S	-135.25 dBmW
Noise ^a power per hertz N	-175.0 dB
SNR per hertz	39.75 dB
Information rate T at 625 bps	-28.0 dB
Available SNR uncoded, ST/N	11.75 dB
Required SNR to achieve a probability of bit error of 10^{-5} using convolutional encoding and sequential decoding	5.0 dB
Signal margin	6.75 dB

^aNoise based on preamplifier temperature of 50 K and antenna temperature of 200 K.

because of the required compression ratio. The approach taken to guard against timing errors was convolutional encoding and sequential decoding (CE/SD). CE/SD will make the pbe in a line of decoded data very low when operating at an SNR of 11.8 dB. If an occasional error does pass the sequential decoder, there are timing checks (described later) after the decompressor that will detect an error.

Required Compression Ratio

A system interface problem developed because the RAE cameras were designed for a previous spacecraft. The camera scan rate and encoder were designed to operate at an output data rate of 20 kbps. To modify the scan rate would have required a camera redesign. Rather than redesigning the camera, it was decided that a data compressor with data storage would be used to process camera information. To meet the telemetry link requirements, a data compressor would be required to have a compression ratio

$$CR = \frac{20\,000}{625} = 32$$

Required Picture Quality

The video bandwidth for the camera scanning rate used is 2.5 kHz. Within the camera encoder, this analog video signal is integrated and sampled at a 5-kHz rate. The sampled video signal is then converted into a digital signal (data) consisting of 4-bit words. As designed, the camera has 15 instead of 16 gray levels per sample, as the zero level is not an allowed state. The video level is adjusted to give the gray-level scale shown in figure 3.

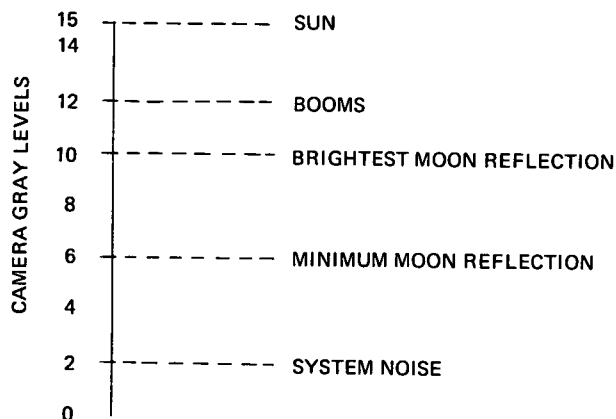


Figure 3.—Expected gray-level scale for RAE B camera.

Compression Technique

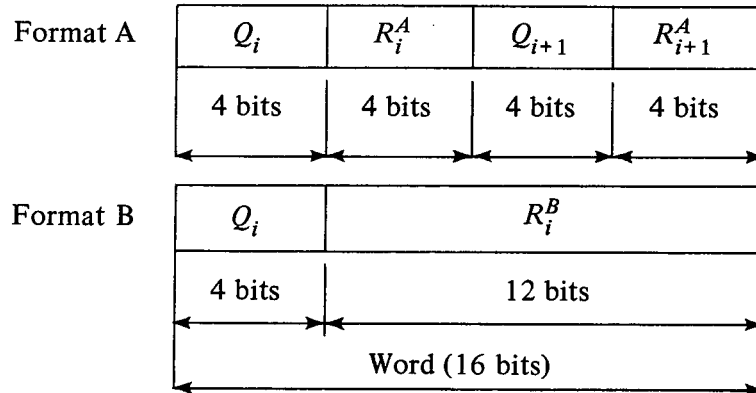
A modified zero-order predictor is used for data compression. The predictor is modified because it has an adaptive run length and aperture. The aperture is related to amplitude information, while the run length relates to timing information. The aperture is an amplitude interval that is predicted to contain the sampled amplitude levels. The aperture size affects resolution in the reconstructed signal. A larger aperture results in poorer reproduction of the original signal. The run length is the number of consecutive amplitude samples within the aperture.

In general, the input to a zero-order predictor is a pulse-code-modulated (PCM) signal which represents data of various amplitudes that have been sampled at a periodic rate. If consecutive sampled points are contained within the aperture (i.e., they are predictable

samples), they are counted. If a sampled point is not contained within the aperture, several operations take place:

- (1) The previous amplitude and accumulated run-length information is transferred out of the predictor.
- (2) A new sample space is defined with the aperture located about the new sampled amplitude.
- (3) The run-length counter is reset to zero.

The zero-order predictor has an aperture that is adaptive to the number of data bits processed per line. The aperture is widened after the number of processed bits exceeds 50 percent of the bits allowable to process a line of camera data. Widening the aperture will, on the average, cause longer run lengths. As modified, the zero-order predictor can operate between two different maximum run lengths, which will result in two different word formats. Selection of the particular operating format is adaptive to the sampled gray level as compared to a given threshold. If the sampled gray level is greater than a given threshold τ , the zero-order predictor operates in format A; if the sampled gray level is less than or equal to τ , the predictor operates in format B. Both formats have 4 bits per word. An example of the two-format system is—



Q_i is the sampled gray level, and the run length R_i is the number of redundant gray levels within a given aperture. Selection of the operating format is based on the first sampled gray level of each word (i.e., the first 4 bits of each 16-bit word).

Timing information need not be transferred with the compressed data for the following reasons: (1) A timing error can be detected if the number of elements of raw data bits per line does not equal the number of reconstructed elements per line, (2) the data are formatted such that a line of video data would be contained within one frame-tree search of the sequential decoder (thus, if uncorrectable errors occur within a line of data, that line could not be decoded; i.e., the sequential decoder could not search the decoding tree), and (3) an error can be detected if the Moon terminator or the booms are not a smooth curve.

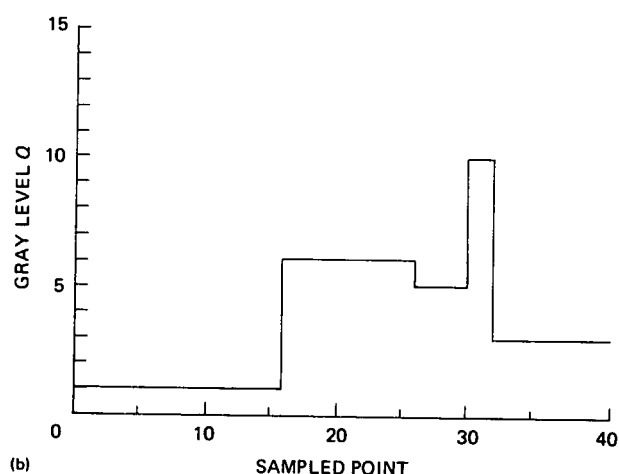
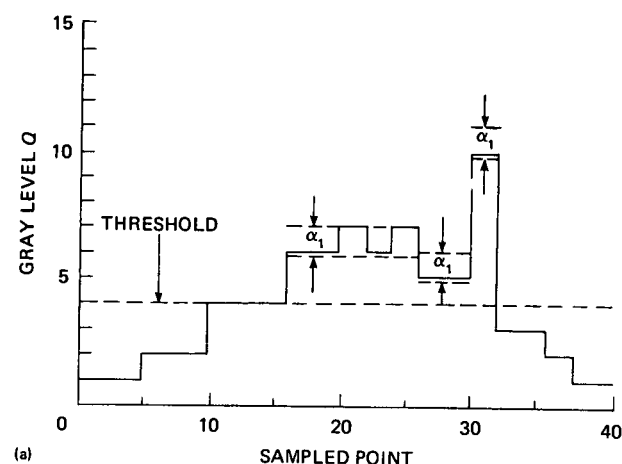


Figure 4.—Example of data-compression technique for $\tau = 4$ and $\alpha = [1, 0]$. (a) Data before compression. (b) Data after reconstruction.

the image-scanner-digitizer field of view was normalized to that of the RAE camera, with the same number of digital words per degree. These digitized data were scaled to yield the expected gray levels shown in figure 3.

Several computer runs were made using the digitized Moon data. Figure 5 shows the maximum number of bits required to process a line of Moon data for various τ and α values. Results from the computer runs were plotted and are shown in figures 6 to 10 (ref. 1). The data shown are from scan line 250, the Moon equator. All other scan lines also were processed and analyzed. Results from these other scanned lines are not shown because on the average they required fewer bits to process than line 250. For comparison, figure 6 shows a plot of the raw, uncompressed Moon data. Note that the resolution of the Moon terminator is not affected by the selection of α and τ levels. The α and τ levels do affect the detail of the Moon craters. The wider the aperture, the greater the data integration.

DATA STUDY BY COMPUTER

A statistical study was made to verify that a compression ratio of 8 is possible when processing a simulated line of RAE B camera data. This study assumed various aperture and threshold levels. The simulated data were obtained from a Moon photograph and by modeling the camera view. Results indicate that a compression ratio of 8 or greater is possible with an aperture α of $[1, 0]$ and a threshold level τ of 4. An aperture α of $[1, 0]$ defines the aperture width of one gray level. The first term, 1, defines the upper gray-level bound with respect to the predicted gray level; and the second term, 0, defines the lower gray-level bound with respect to the predicted gray level. For an example showing data compression techniques with τ of 4 and α of $[1, 0]$, see figure 4.

Moon statistics were obtained from a computer study. The computer was programmed to process data in the same manner as the modified zero-order predictor. The data processed by the computer were obtained from a Moon photograph, which was optically scanned and digitized. The Moon photo was reduced in size so that

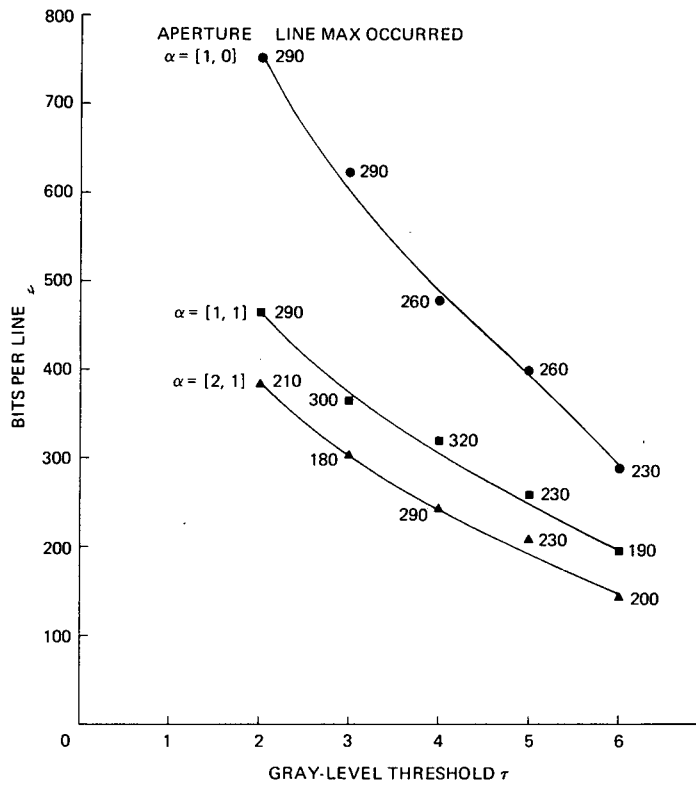


Figure 5.—Maximum number of bits required to process a line of Moon data for various τ and α values.

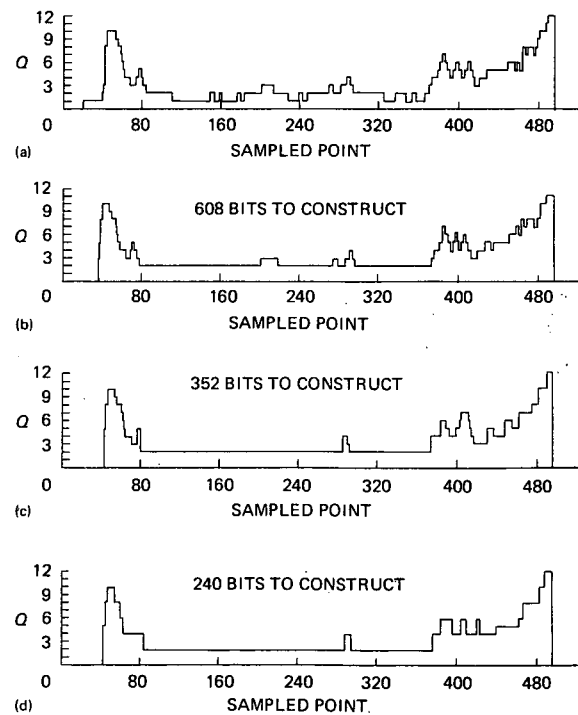


Figure 6.—Gray level Q versus time for Moon profile line 250, $\tau = 2$. (a) Raw data. (b) Reconstructed, $\alpha = [1, 0]$. (c) Reconstructed, $\alpha = [1, 1]$. (d) Reconstructed, $\alpha = [2, 1]$.

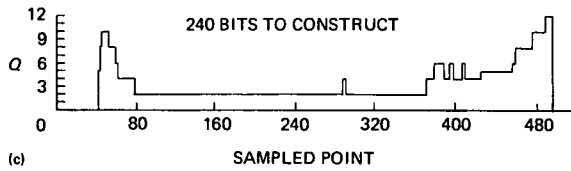
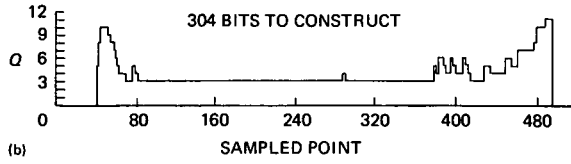
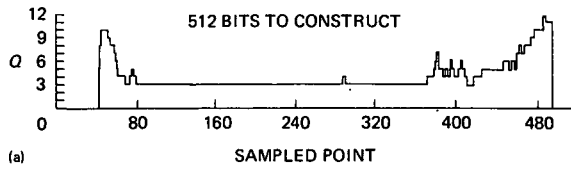


Figure 7.—Gray level Q versus time for Moon profile line 250, $\tau = 3$. (a) $\alpha = [1, 0]$. (b) $\alpha = [1, 1]$. (c) $\alpha = [2, 1]$.

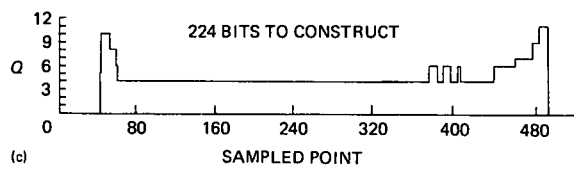
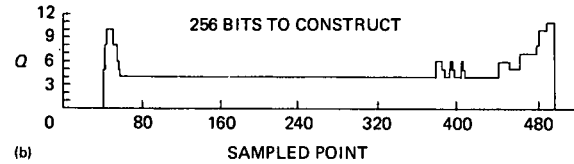
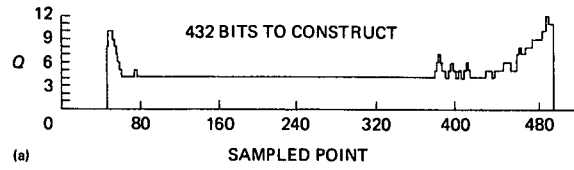


Figure 8.—Gray level Q versus time for Moon profile line 250, $\tau = 4$. (a) $\alpha = [1, 0]$. (b) $\alpha = [1, 1]$. (c) $\alpha = [2, 1]$.

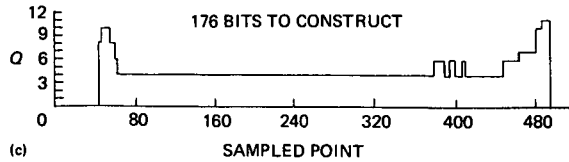
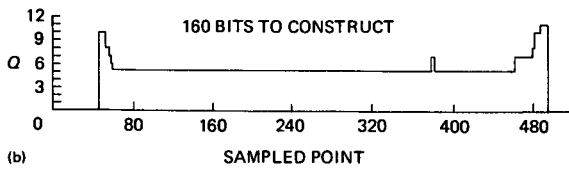
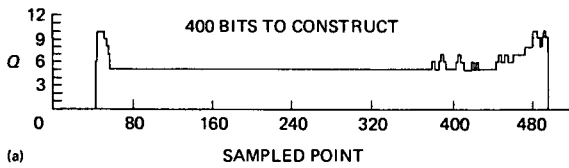


Figure 9.—Gray level Q versus time for Moon profile line 250, $\tau = 5$. (a) $\alpha = [1, 0]$. (b) $\alpha = [1, 1]$. (c) $\alpha = [2, 1]$.

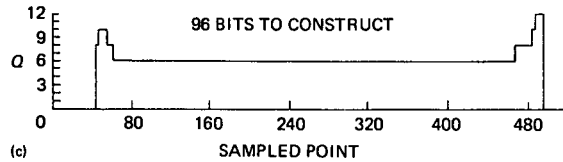
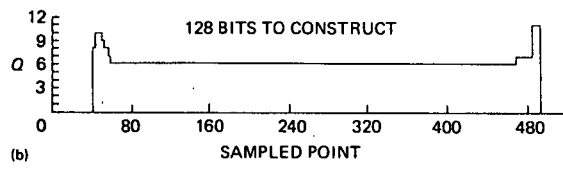
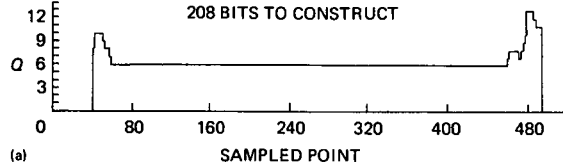


Figure 10.—Gray level Q versus time for Moon profile line 250, $\tau = 6$. (a) $\alpha = [1, 0]$. (b) $\alpha = [1, 1]$. (c) $\alpha = [2, 1]$.

Results of these tests indicate that a compression ratio of 8 is possible when processing the RAE B camera data. With $\alpha = 2$ and $\tau = 4$, 320 bits would be required to process a line of Moon data at the equator. This would leave 704 bits to process the remaining details of the line. The maximum number of bits required to process the Sun, Earth, booms, and paddles as shown in figure 2 at line 512 is 672 bits. This leaves approximately 332 bits to process the Moon at this latitude.

AAP SYSTEM

Figure 11 shows a block diagram of the AAP. The AAP system is configured with an input buffer, data compressor, sector memory, output buffer, convolutional encoder, command decoder, and command storage circuitry. Input data to the AAP are from the camera encoder and from the spacecraft command subsystem. The processor outputs are serial PCM data which are convolutionally encoded at 1250 symbols per second and serial PCM data to the spacecraft telemetry subsystem at 200 bps. The convolutionally encoded data are processed camera data, while the telemetry data verify the command memory status.

Data input to the AAP from the camera encoder is processed by the AAP as the data are received (in real time). The real-time processing includes data compression. When using the modified zero-order predictor, a compression ratio of 8 is possible. Therefore, an overall compression ratio of 32 can be obtained when data compression is performed on every fourth camera scan line. Processing every fourth line of the 70° elevation coverage will result in the system acquiring Moon versus spacecraft attitude to 1.0° accuracy (ref. 2).

During a camera scan, data from selected areas of the camera field of view are stored in the AAP memory. These stored data contain information from four small sectors (fig. 12). Each sector contains the area in which each of the four boomtip targets are expected. The

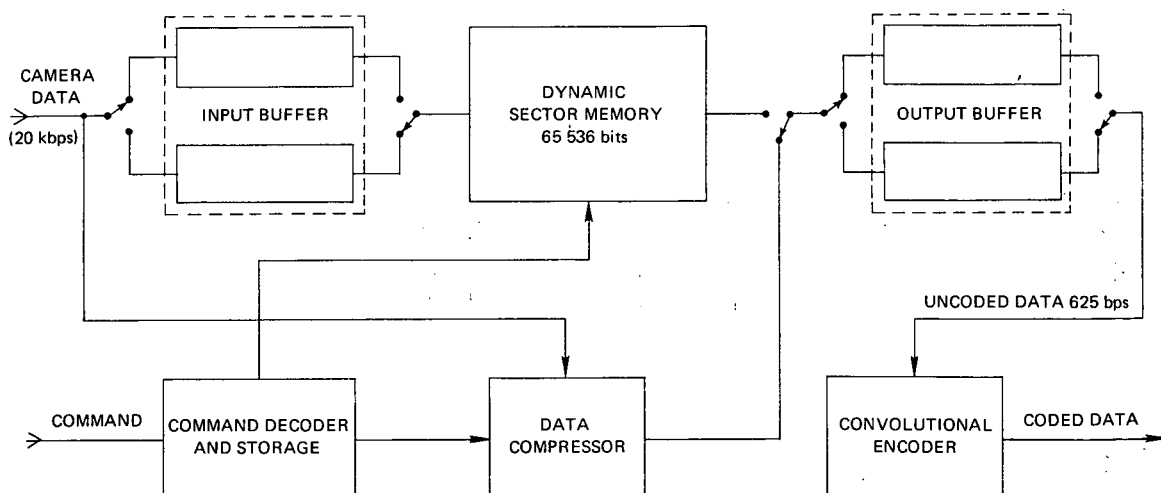


Figure 11.—AAP block diagram.

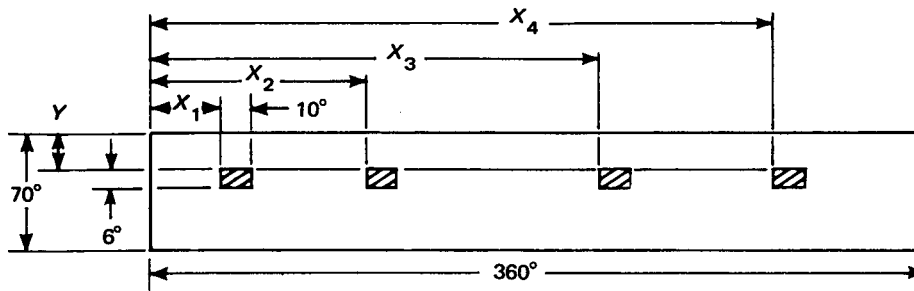


Figure 12.—Camera field of view showing four sectors.

approximate area of each sector is 10° (256 bits) by 6° (64 lines). Location of each sector is selectable by commanding the X , Y coordinates of the first element of the sector to be stored as shown in the figure. The Y coordinate is common to each sector because the two sets of V booms are in the same plane and only a small displacement out of this plane is expected. The stored sector data contain consecutive scan lines and are not compressed. These sector data will resolve in two planes the position of the boomtip targets to within 0.35° .

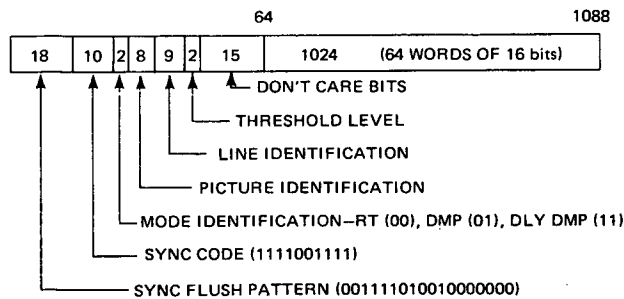
Sector data can also be stored while the spacecraft is occulted by the Moon. In this mode, the camera system will turn on by a delayed command from the spacecraft programmer. After the sector data are stored, the camera is internally programmed to shut off. The memory unit is powered until after the memory data are telemetered to a ground station.

Data Compressor

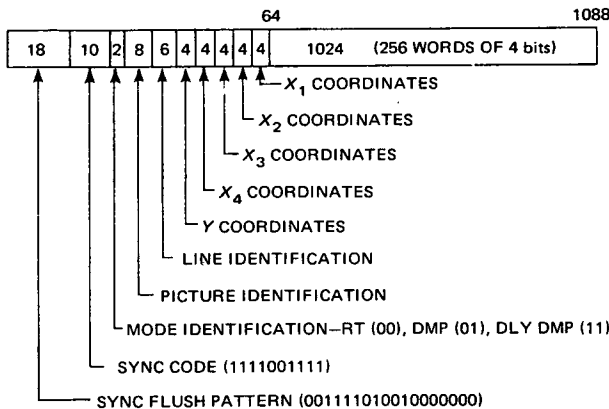
Input to the data compressor from the camera encoder is serial PCM signal at 20 kbps. Each line of camera data contains 2048 4-bit words plus line and subline synchronization and identification data. The data compressor processes every fourth line of camera data into 1024 data bits starting with line 3. The compressor adds a 64-bit header to each line of processed data. This header contains line number, mode of operation, operating threshold, frame synchronization, and flush patterns as shown in figure 13.

The data compressor was designed as a two-format system. The operating format is a function of τ and the sampled gray level. The threshold level can be changed by means of a ground-station command to one of four Q values (2, 3, 4, and 5). Characteristics of the two-format system follow:

- (1) Each format uses an input of 16-bit words.



(a)



(b)

Figure 13.—Formats of uncoded output data from compressor. Both formats use 16-bit words, with 68 words per frame, and 1.7403 s per frame. (a) Search mode, 128 frames per picture. (b) Dump mode, 64 frames per picture.

the buffer is 75 percent full, α is widened to $[2, -1]$ about the predicted gray level. If the sampled gray level is less than or equal to τ , the value of α is $[\tau, 0]$ and the aperture width does not depend on the percent of data contained in the output buffer.

The data compressor was built with 47 integrated circuit modules using complementary metal oxide semiconductor (CMOS) devices. Figures 14 and 15 present flow diagrams for the compressor.

Sector Memory

Data from the camera encoder are wired to the data compressor and also to the sector memory. During the camera scan, sector data are gated into the memory at selected intervals. After the camera scan, the AAP generates a camera shutoff pulse, and then the memory is read out at 20 kbps into the buffer.

Data to be stored are determined by means of a ground command which gives the X , Y coordinates of the sector end points. Each sector is approximately 10° by 6° (256 bits by

- (2) Operating format is based on a comparison of the first 4 bits of each 16-bit word to the value of τ . If the sampled gray level is greater than τ , the word format has alternating 4 bits of gray-level information followed by 4 bits of maximum run length. If the sampled gray level is less than or equal to τ , the word format has 4 bits of gray level followed by 12 bits of maximum run length.

The data-compressor-aperture width is made adaptive to the amount of data contained in the output buffer. The adaptive aperture controls the data flow into the output buffer. Widening the aperture results in longer run lengths because the predicted gray-level area is larger.)

The aperture width is a function of τ and the percent of data in the output buffer. When the sampled gray level is greater than τ , the aperture α is set to $[1, 0]$ about the predicted gray level. This α setting is used until the output buffer is 50 percent full, at which time α changes to $[1, -1]$. When

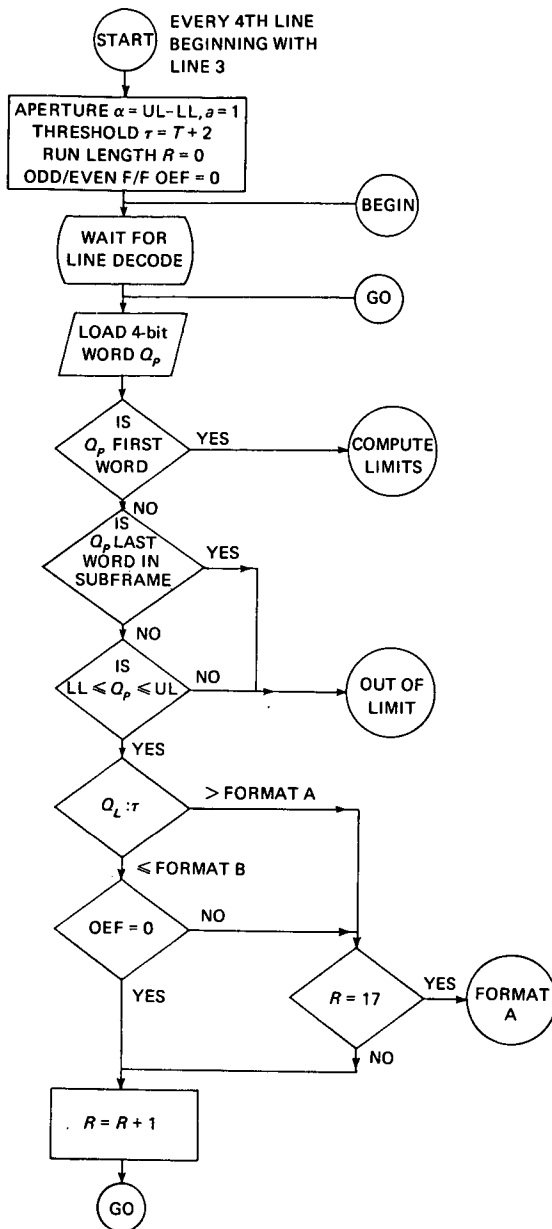


Figure 14.—Data-compressor flow diagram.

the sector memory or from the data compressor. The buffer provides a continuous data flow at 625 bps into the convolutional encoder. Data are received from sector memory in bursts of 1024 bits at 20 kbps, whereas the data flow from the data compressor occurs in bursts of 8 or 16 bits.

Convolutional Encoder

The convolutional encoder accepts a continuous data flow at 625 bps from the output buffer. These data are convolutionally encoded into 1250 symbols per second (sps) which

64 lines) and can be programed to any location within a 70° by 90° area of the camera field of view.

The sector memory capacity is 65 536 bits. This capacity is required because each sector contains 16 384 bits (256 by 64 lines). No synchronization or identification data are stored. The header with synchronization and identification data is added during memory playback as illustrated in figure 13.

The sector memory consists of a static input buffer and a dynamic memory. The input buffer contains two 1024-bit, static shift registers using CMOS devices. Two static shift registers are required so that one register can hold data while the dynamic memory is being accessed and the other register is storing incoming camera data. Each static register has enough capacity to fill one dynamic memory element.

The dynamic memory contains 64 dynamic, 1024-bit shift-register elements. Organization of the memory is such that each memory element is addressed individually and in sequence. Should any one element fail, only 1/64 of the memory capacity is lost. Each element has the capacity to store one line from each of the four sectors. These elements are P-channel metal oxide semiconductor devices that require 7.3 μW per bit when clocked at 20 kHz.

Output Buffer

The output buffer accepts data from either

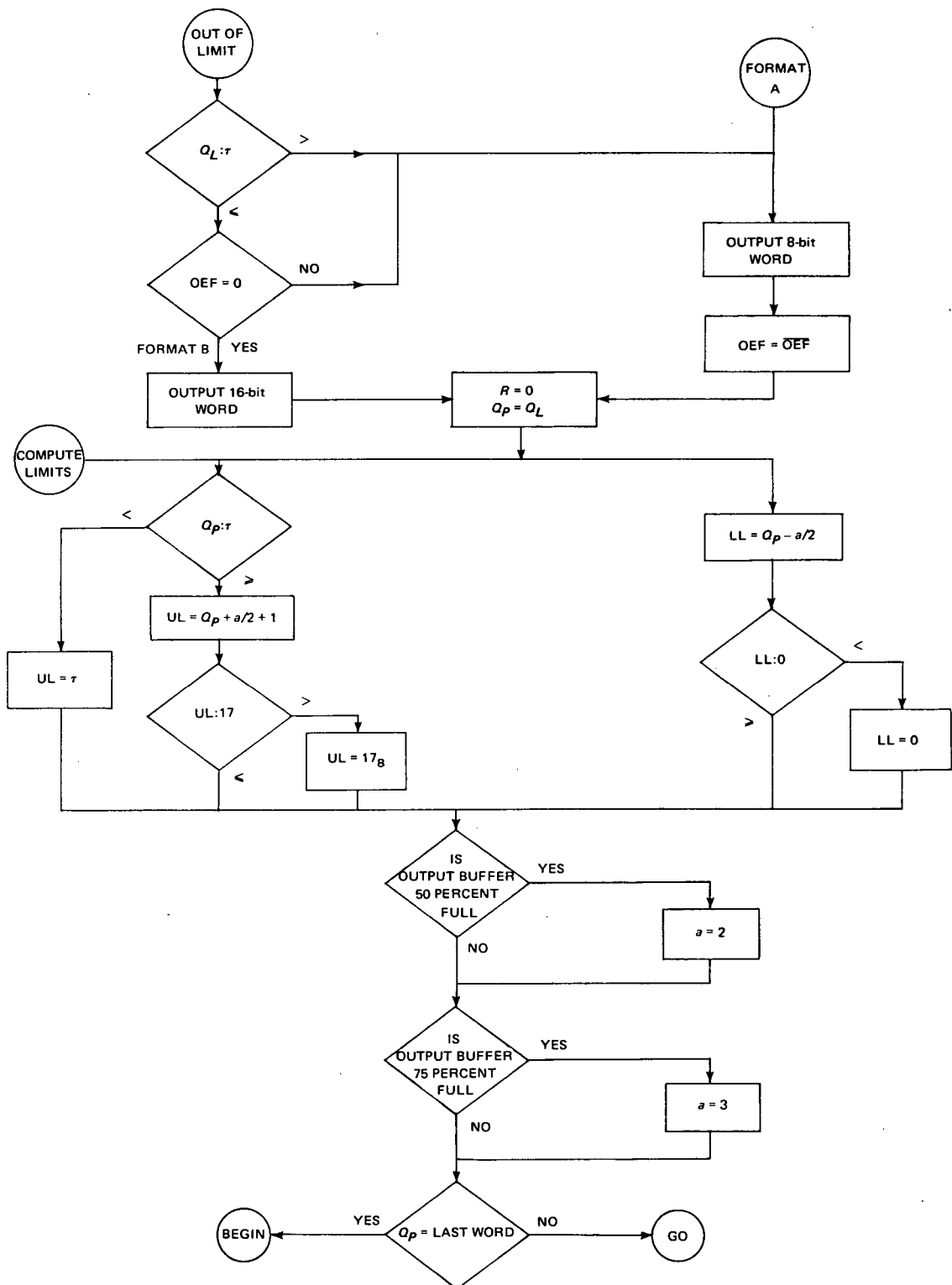


Figure 15.—Data-compressor-limits flow diagram.

are then converted into the biphasic PCM signal required to phase modulate the transmitter's carrier.

The encoding used is referred to as a systematic (36, 18) code. Truncations of two generator functions specified by James Massey are used to generate parity bits (ref. 3). The truncated generators are—

$$G_1 = (733533)_8$$

$$G_2 = (533533)_8$$

The encoder is flushed with a known pattern at the end of each data frame. This flush pattern enables the sequential decoder to complete its tree search with data from the tail of the frame and it provides a known initial condition for the encoder prior to the entry of the frame synchronization generator pattern. Figure 13 shows the flush and frame-synchronization generator patterns.

Given the specified code generators and flush and frame generator patterns, the encoder will output the frame synchronization pattern—

111110011101000000

This pattern assumes that parity bits which are generated with G_2 are complemented and that G_2 is sampled before G_1 . The G_2 parity bits were complemented to aid in bit synchronization at the ground processor. That is, by complementing G_2 parity bits, a longer string of zero data bits into the encoder will yield an alternating 1010 pattern at the encoder output.

The convolutional encoder was built with eight CMOS integrated circuit modules. Figure 16 gives the logic diagram for the encoder.

Command Storage

Two types of commands control the AAP: The operation commands determine the operational sequence of the AAP, and the coordinate and threshold commands determine the sector location and the operating threshold of the data compressor.

Operation commands originate at the spacecraft-control logic programmer. These commands are labeled C60 and T3. When the AAP receives a C60 command, one camera picture is processed and the memory is played back. After the memory is dumped, the AAP is internally programmed to shut off its own power. When a T3 command is received, the AAP operates as before except that the unit shuts off only the camera. The AAP remains powered until a C60 command is received, at which time the memory is dumped and the unit is shut off. A T3 command is used whenever sector data are required for a period when the spacecraft-to-Earth communication link will be occulted by the Moon.

Coordinate and threshold commands originate from the spacecraft bus box. These commands are PCM signals with a "zero" bit command (CMD0) and a "one" bit command (CMD1). Each command (i.e., CMD0, CMD1) is wired from the bus box to the AAP on

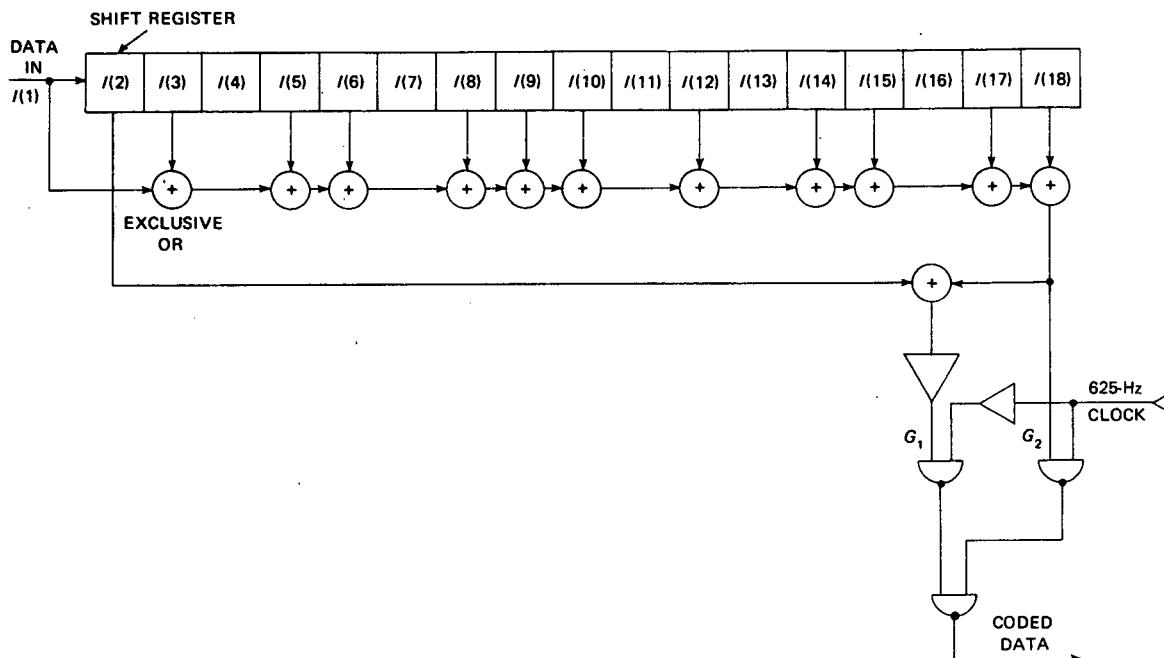


Figure 16.—Convolutional encoder logic diagram.

separate lines. A command pulse is sent on the CMD0 line if a zero bit is desired for a particular bit position and a command pulse is sent on the CMD1 line if a one bit is desired. The commands from both the CMD0 and CMD1 lines are logically OR'd to form a 22-bit command word. This command word determines the threshold of the data compressor and the coordinates of the sector starting points. The 22-bit word format is—

$$T_2 T_1, Y_4 Y_3 Y_2 Y_1, X_4^4 X_3^4 X_2^4 X_1^4, X_4^3 X_3^3 \dots, X_4^1 X_3^1 X_2^1 X_1^1$$

These 22-bit command words are stored in a CMOS device memory within the AAP which is powered continuously, even when the AAP power is off. For this operation, the CMOS memory requires 6 mW. For proper operation, these commands should not be altered while the AAP is processing data. Verification of the commands is accomplished via the spacecraft telemetry system.

Physical Parameters

A block diagram of the AAP is shown in figure 11. The entire processor contains 309 individual integrated circuits which are mounted on five fiber-glass boards (fig. 17). Components are connected by either printed circuit material or micropoint interconnect welding. This hybrid interconnecting technique lends itself to versatility and high-density packaging.

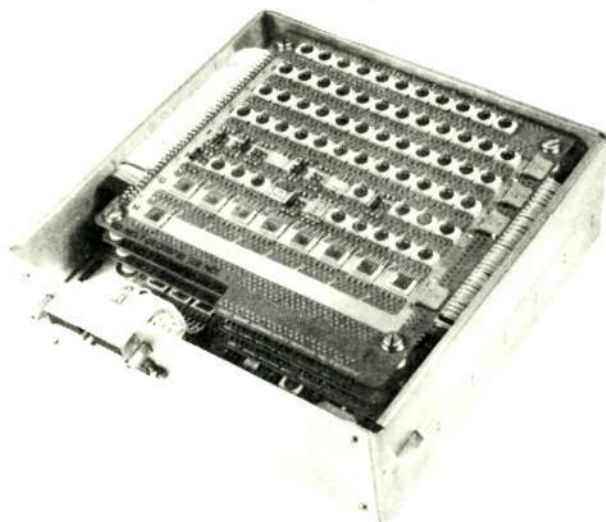


Figure 17.—The fabricated AAP unit.

Except for the memory elements and a few field-effect transistor switches, all logic elements are CMOS devices. These devices were used because of their low standby power per gate.

The AAP including memory requires a volume of 2048 cm^3 (125 in^3), has a mass of 1.36 kg (3.0 lb), and consumes less than 1 W in operation. The unit is designed to function between the temperatures of 263 K (-10°) and 323 K (50°C) and will withstand the expected RAE B launch environment. This unit was checked with a ground computer (ref. 4) over the environmental temperature range.

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